Department of Energy
Washington, DC 20585

APR 3 0 1998

The Honorable John T. Conway
Chairman
Defense Nuclear Facilities Safety Board
625 Indiana Avenue, NW
Suite 700
Washington, DC 20004

Dear Mr. Chairman:

Enclosed is the DRAFT Department of Energy Standard, "Criteria for Packaging and Storing Uranium-233 Bearing Materials." It represents the deliverable for Commitment 2 of the Department's Implementation Plan for addressing the Defense Nuclear Facilities Safety Board's Recommendation 97-1 concerning the safe storage of Uranium-233 material.

Along with transmittal to the Board, the Draft Standard is concurrently being processed through the DOE Technical Standards Program for DOE Complex-wide review and comment.

We have completed the actions identified under this milestone and propose closure of this commitment. If you have any questions, please contact me, or have your staff contact Hoyt Johnson of my staff at (202) 586-0191.

Sincerely,

David G. Huizenga
Acting Deputy Assistant Secretary for
Nuclear Material and Facility Stabilization
Office of Environmental Management

Enclosure

cc: (w/encl)
M. Whitaker, S-3.1

DRAFT

DOE STANDARD (DRAFT)
Criteria for Packaging and Storing Uranium-233-Bearing Materials

April 22, 1998

FOREWORD

This Standard establishes the criteria for the safe packaging and storage of Uranium-233(^{233}U)-bearing materials and aims to obviate subsequent repackaging during their storage or for possible transport from their existing storage facilities until their respective dispositions are identified. Materials conforming to these criteria should be contained and stored safely for at least 50 years (pending disposition). Periodic inspections of ^{233}U packages must be conducted in order to confirm the storage lifetime objectives covered by this Standard. The justifications and bases for the criteria are given in Appendix C. This Department of Energy (DOE) Standard is approved for use by all DOE components and their contractors.

The Department of Energy (DOE) was producing special nuclear materials (SNM) in their purest forms for weapons production and reactor fuel fabrication during the Cold War period. Typically the SNM, which includes plutonium-239 (^{239}Pu), enriched uranium-235 (^{235}U) or ^{233}U, were either in the forms of metals or relatively pure oxides. These SNM materials were also the most "attractive" from a safeguards perspective because they could most readily be used to fabricate nuclear weapons.

The DOE mission has been refocused in the past few years to emphasize weapons dismantlement, safe fissile materials storage and disposition of excess SNM to Departmental needs, while preserving a reduced stockpile. Aside from weapons dismantlement and production activities, significant quantities of Departmental fissile materials, also exist in a variety of chemical forms from fuel cycle programs and from other nuclear research and development (R&D) projects. These materials must be safely stored in the interim until their ultimate dispositions are identified. Coincidentally, safeguards and nonproliferation concerns must be considered. Safe storage of these reactive materials is the current end-point for the SNM inventories prior to disposition.

Existing Departmental storage facilities at ORNL and INEEL will be used for storage of the ^{233}U materials since future needs/uses for the materials have not yet been completely identified. The major safety elements in the storage of unirradiated ^{233}U are preventing criticality, containing radioactive materials, protecting personnel from penetrating radiation, and safeguarding this special nuclear material. Except for containing radioactive materials, the storage facility plays a primary role in addressing these safety elements. The facility also plays a principal backup role (i.e., defense in depth) in confining radioactive contaminants during upset conditions. Material stabilization, consolidation, access limitation, low maintenance storage and reliability in verification of the inventory are the Department's present goals for the ^{233}U-bearing materials.

DOE technical standards do not by themselves establish mandatory requirements. However, all or part of the provisions in a technical standard can become requirements under the following circumstances:

(a) they are explicitly stated to be requirements in a DOE requirements document; or

(b) the organization makes a commitment to meet a standard in a contract or in a plan or program required by a DOE requirements document.

Throughout this Standard, the word "shall" is used to denote actions that must be performed if this Standard is to be met. If the provisions in this technical Standard are made mandatory through one of the two ways discussed above, then the "shall" statements become requirements.

TABLE OF CONTENTS

1. INTRODUCTION

1.1 Purpose and Scope

This Standard provides criteria for safely packaging and storing ^{233}U-bearing solid materials for at least 50 years without subsequent repackaging. Periodic inspections of ^{233}U packages must be conducted in order to confirm the storage lifetime objectives covered by this Standard. This Standard does not apply to the packaging of uranium-bearing liquids, uranium-bearing material with less than 1% by weight ^{233}U, designated wastes, irradiated materials, in-process materials, or small quantities involved in research and development studies.

A majority of the ^{233}U in inventory consists of mixtures of ^{233}U and ^{232}U or mixtures whose properties are dominated by the ^{233}U and ^{232}U content. These materials have substantially different radioactive and nuclear characteristics than the other two Special Nuclear Materials (SNMs), ^{235}U and ^{239}Pu. For example, the ^{232}U decay chain produces ^{208}Tl, which emits a 2.6 MeV gamma-ray. This highly energetic gamma-ray and the high alpha activity associated with ^{232}U necessitate facility safety characteristics such as shielding in addition to material and packaging considerations for safe storage. Therefore, guidance for facility features addressing the unique properties of ^{233}U is provided in this Standard.

Safeguards and security interfaces, and packaged materials transportation criteria and requirements are addressed in detail by other specific DOE directives (e.g., rules, orders) and other Federal agencies' directives. These are not repeated in this Standard. Users of this Standard, however, are advised to consult and assure adherence with other applicable directives while implementing these criteria. It is the responsibility of the organization in custody of the material to provide safe conditions for handling and storing the material.

1.2 Equivalency

This Standard allows using systems, methods, material forms, or devices that are functionally equivalent or superior in the place of those prescribed herein if demonstrated by technical documentation.

2. DEFINITIONS

Terms and acronyms applicable to this Standard and to the criteria bases are listed and defined in Appendix B.

3. REFERENCES

Specific DOE and other Federal agency regulations and other documents used in developing this Standard and the bases for the Standard are listed in Appendix C.

4. MATERIAL AND PACKAGING CRITERIA

The following criteria are established to control potential hazards to workers, the public and the environment for packaging and safely storing unirradiated ^{233}U-bearing materials. Technical bases for the criteria are provided in Appendix A. Besides conforming with these safe storage criteria, the reader should review other specific DOE directives which address SNM issues, e.g., orders on nuclear materials control and accountability (NMC&A), radiation protection controls, criticality and transportation.

4.1 Material Quantities

a. Criticality limits shall be addressed through Nuclear Criticality Safety Approvals (NCSAs) for storing fissile materials in excess of the minimum critical masses listed in ANSI/ANS-8.1. (See Section 5.1)

b. The mass of ^{233}U fissile material, per storage container, should be less than 0.4 kg (0.88 lb_m) for metals and 2.0 kg (4.4 lb_m) for oxides (including oxide powders, oxide monoliths, and ceramic oxides), unless enhanced security provisions are afforded for handling and storing individual packages containing larger quantities.

4.2 Material Criteria

Storable ^{233}U-bearing solid forms include metals, alloys, oxide powders, oxide monoliths, and ceramic oxide pellets.

4.2.1 Metals and Alloys. Metal and alloy pieces shall have a specific surface area of less than 50 cm^2/g. Particles and metal pieces larger than 8 mesh (2.38 mm) meet this criterion. Metal pieces with a specific surface area greater than 50 cm^2/g, thin foils, and turnings should be thermally stabilized to oxides for storage. Loose oxide on outer surfaces of metal pieces shall be removed prior to packaging metals for storage.

4.2.2 Separated Oxide Powders. Stored materials may include oxide powders of ^{233}U and mixed uranium isotopes. These materials shall be thermally stabilized to remove moisture and to convert residual salts to oxides.

4.2.3 Oxide Monoliths. Monoliths are large, brick-like pieces of oxide, typically U_3O_8, which have been calcined at greater than 700 °C for at least one hour to ensure that there is no residual moisture or salt in the material. The criteria for storing oxide monoliths of ^{233}U are less constraining than for ^{233}U oxide powders because their prior processing operations resulted in a more stable physical form.

4.2.4 Ceramic Oxides. Ceramic mixed oxide pellets are high-fired ceramic matrices. They are very stable since the temperature reached during their formation is high enough to ensure that there is no residual moisture or salt in the material. Storage criteria for ceramic ^{233}U mixed oxide forms (pellets and sintered fuel) are less constraining for safety because their prior processing operations and chemical compositions result in more stable physical forms, provide added self-shielding, criticality constraints, and contamination controls.

4.3 Packaging for Storage

A minimum of two barriers are required to isolate stored ^{233}U materials from the environment (Fig. 1). Packaging provides a principal barrier for isolating stored material from the environment. As such, it should be designed to maintain mechanical integrity, including closure, during anticipated handling and storage operations. General issues surrounding the package relate to material of construction, internal package atmosphere, identification and closure. The storage package for metals and powders shall consist of a minimum of two containers to isolate the stored materials from the environment and to prevent the release of contamination. However, it is recognized that the fuel material form (e.g., ceramics) or the facility may, in some cases, provide one or both of these isolating barriers. Sections 4.3.1, 4.3.2, 4.3.3, and 4.3.5 do not apply to ceramic material. Sections 4.3.2 and 4.3.6 do not apply to oxide monoliths.

4.3.1 General Requirements. The following apply to required containers used in packaging:

a. Shall be fabricated of inorganic materials that are resistant to corrosion due to contact with the material and the anticipated storage environment. It is recognized that stainless steel, aluminum, zirconium alloys, and nickel-based alloys are considered resistant to corrosion in most applications.

b. Shall contain a non-corrosive atmosphere (e.g., nitrogen or inert gas for metals and oxides; oxides may also be packaged in ambient air).

c. Shall have permanent (e.g., etched, engraved, or stamped) identification markings.

d. Shall be sealed.

4.3.2 Inner Container. The inner container, if required, shall be sized to fit into an outer container (with clearance for optional welding, if applicable). At ORNL, the inner container diameter also shall be no greater than 8.6 cm. (3.375 in. I.D.).

4.3.3 Outer Container. The following apply to the outer container:

a. Shall be sized to fit into the storage configuration. A maximum container height may be specified but would be related to physical handling operations and compatibility with transport casks.

b. Contamination of the exterior surface shall conform to the limits specified in 10 CFR 835.

c. The outer container should have structural rigidity meeting acceptance criteria that satisfies anticipated package storage conditions.

4.3.4 Optional Container(s). Additional layers of packaging are permitted if they adhere to the Inner Container requirements (Section 4.3.2). The use of additional containers, sometimes referred to as "material" or "convenience" containers, is optional.

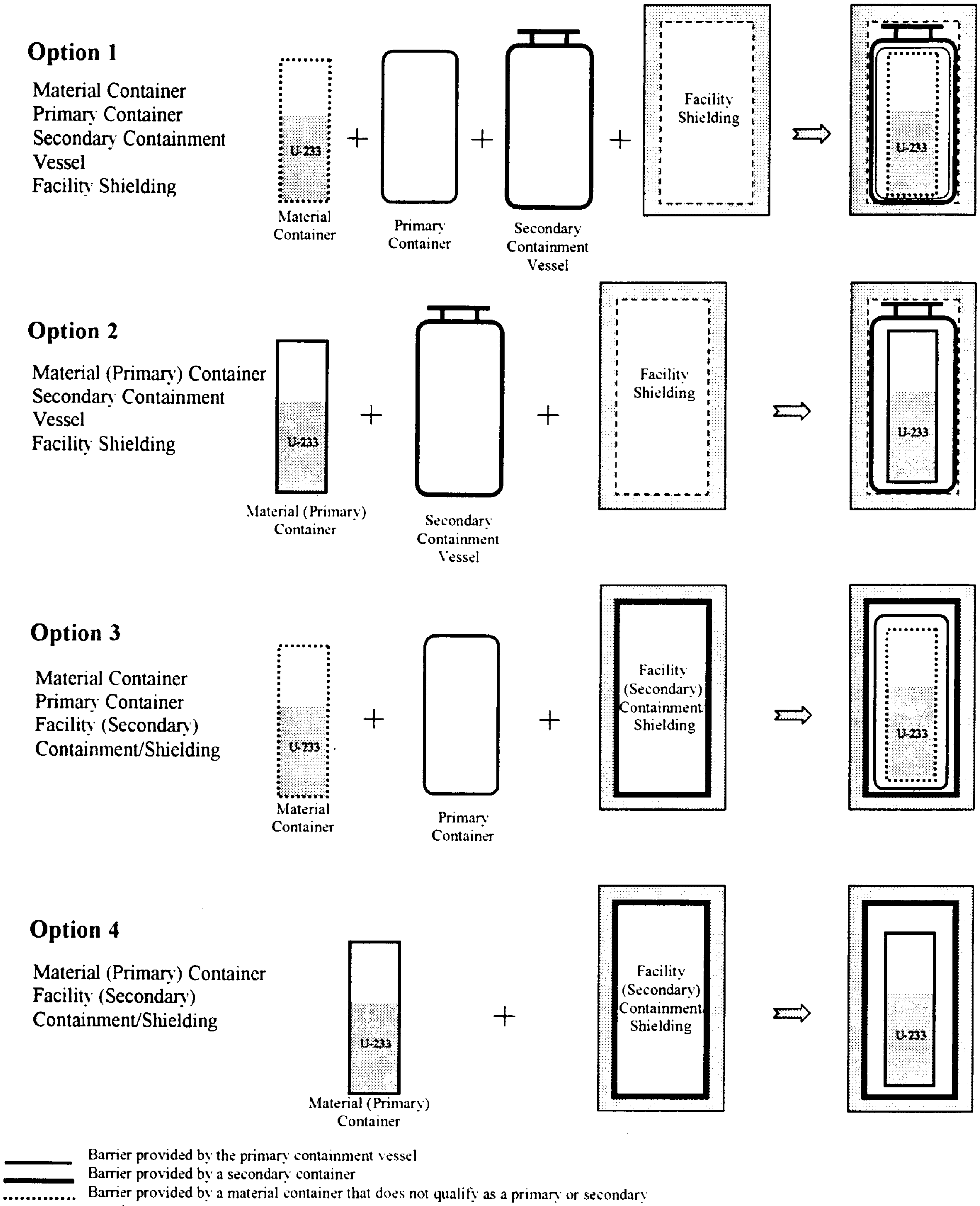

Fig. 1. Package configurations for safe storage of ^{233}U.

4.3.5 **Oxide Monoliths.** For oxide monolith materials, where the primary barrier is a brick-like monolithic oxide matrix, the material can be stored in less demanding packaging than must be used with metals or oxide powder. The second barrier is provided by a container layer(s) that meets the provisions of Sections 4.3.1 and 4.3.3.

4.3.6 **Ceramic Fuel Materials.** For ceramic fuel materials where the primary level of containment is the robust, high-fired ceramic matrix of the fuel pellet, the material can be stored in less demanding packaging than must be used with metals or the lower temperature-formed oxide powder. The container can be closed either by a screwed-on lid on a 2R container inside a 6M drum or a bolted-on lid stored in a storage vault. The following apply to the storage containers:

a. The containers shall be fabricated of or coated with materials that are resistant to corrosion in the anticipated storage environment.

b. The containers shall have permanent (e.g. etched, engraved, or stamped) identification markings.

4.4 Inspection and Surveillance for Safety

Inspection and surveillance procedures shall be site-specific, shall incorporate ALARA exposure considerations, and should identify:

a. Prerequisites;

b. Acceptance criteria;

c. Specific instructions to ensure that items not meeting acceptance criteria are addressed in accordance with approved procedures and DOE reporting requirements; and

d. Frequency for surveillance for safety.

4.4.1 **Documentation of inspection and surveillance methods.** Formal methods and responsibilities shall be documented and maintained for independent review and evaluation.

4.4.2 **Surveillance Plan.** The surveillance plan should include provisions for:

a. Initial baseline package inspection after an appropriate initial delay interval after packaging;

b. Periodic surveillance throughout the storage period. Surveillance frequency, sample population, and package selection should be established by a statistical approach;

c. These inspections should integrate safety (e.g., evaluation of indications of container deformation) and MC&A requirements (DOE 5633.3B).

4.5 Documentation

4.5.1 **Database.** A database shall be maintained to serve as a source of relevant information about the stored materials and packages. For completeness, MC&A documentation should be coordinated with the database.

4.5.2 **Database Requirements.** The database should include:

a. Identification of the following material characteristics:
   1) Chemical composition.
   2) Physical form (e.g., ^{233}U metal, oxide powder, monolith, or ceramic).
   3) Elemental concentration or mass.
   4) Fissile isotope fraction or ^{232}U fraction (in ppm).
   5) Source of stored material (facility that prepared the material in its current form).
   6) Specific processing condition(s).
   7) Moisture content
   8) Other information relative to the contents (e.g., major impurities, radiation level).

b. Identification of the following package characteristics:
   1) Fill gas on sealing.
   2) Package configuration - number of inner containers in package.
   3) Date of packaging.
   4) Initial radiation field [gamma and neutron radiation levels at contact and 30 cm (12 in)].
   5) Baseline package weight and outer dimensions.

c. Records of the inspections performed, names of individuals performing inspections, and dates of inspections. Historical records on packages shall be maintained for the life of the packages.

d. Location(s) of stored materials.

4.6 Quality Assurance/Control Requirements

4.6.1 All personnel participating in essential processes and procedures shall be trained and qualified.

4.6.2 Materials used in the fabrication and sealing of repackaging containers shall satisfy all specifications necessary to comply with the requirements of these criteria.

4.6.3 Procedures and processes that are essential for assuring compliance with these criteria shall be subject to Quality Assurance (QA) per 10 CFR 830.120 and Quality Control (QC) Procedures.

4.6.4 Essential procedures and processes covered by QA and QC requirements shall include (but will not be limited to):

a. Thermal stabilization procedure;

b. Sealing (e.g., welding) procedure used in container fabrication and closure;

c. Surveillance procedure(s); and

d. Database recording procedure and characterization parameters addressed in Section 4.5.2.

5. STORAGE FACILITY FEATURES

A facility used for the storage of ^{233}U should address the unique characteristics of the material and include nuclear criticality safety, confinement of radioactive materials, radiation shielding, and safeguarding Special Nuclear Material (SNM).

5.1 Nuclear Criticality Safety

For storing fissile materials in excess of the minimum critical masses listed in ANSI/ANS-8.1, NCSAs shall be obtained for the specific ^{233}U-bearing material storage configuration and for the specific operations required to store the ^{233}U-bearing material in that configuration. In addition to providing an array that is initially criticality safe, the facility must be engineered to avoid the occurrence of a criticality incident under upset conditions such as fires, dust explosions, flooding, earthquakes, and tornadoes. These NCSAs must consider the presence of other fissile isotopes, and materials such as low-Z materials, plastics, and moisture, which potentially affect criticality. The material may contain neutron absorbers (i.e., gadolinium and cadmium), that may be taken into account in the NCSAs.

The risk of nuclear criticality is managed by application of the double contingency principle, which requires that at least two unlikely, independent, and concurrent changes in storage conditions must occur before critical configuration can be reached.

5.2 Confinement of Contamination

The material containers or containment vessels serve as the principal barrier for confinement of contamination. Depending on the material storage system, the facility itself may serve as another confinement barrier. The combination of the material storage system and the storage facility represents a defense-in-depth confinement system.

5.2.1 Facility Confinement. The facility where ^{233}U-bearing material is stored provides a physical barrier to the release of contamination. In order to prevent and/or mitigate the consequences of all accidents including bounding design basis and criticality accidents, and to ensure compliance with storage facility related requirements and regulations, the following criteria apply:

a. The facility shall meet the applicable and enforceable requirements for readiness assessments specified in DOE O 425.1, Startup and Restart of Nuclear Reactors.

b. New or modified ^{233}U-bearing material storage systems, components, and structures shall meet design criteria requirements specified in DOE O 420.1 and DOE O 430.1 (when implemented).

c. Uranium-233-bearing material storage facilities shall meet the National Fire Protection Association (NFPA) standards, as applicable (DOE O 420.1).

d. Uranium-233-bearing material storage facilities shall meet the requirements for safety analysis as specified in DOE 5480.21, DOE 5480.22, and DOE 5480.23 (to be replaced by the appropriate section of 10 CFR 830 when promulgated).

e. Current ^{233}U-bearing material storage facilities shall be evaluated for design criteria compliance specified in DOE O 420.1.

f. The facility shall meet the applicable and enforceable requirements for protection of the environment as specified in DOE 5400.1, DOE O 231.1, and DOE M 231.1.

5.2.2 **Ventilation**. The ventilation system of the storage facility promotes confinement by ensuring air flow from clean to contaminated area, then to air filters. The design and safety aspects of a ventilation system for storage of ^{233}U bearing materials are as specified for facility confinement in section 5.2.1. In addition, the requirements for stack emissions in 40 CFR 61, Subpart H shall also be met.

5.3 Radiation Shielding

Owing to the presence of ^{232}U in ^{233}U inventories, radiation shielding is required to attenuate the 2.6 MeV photon emitted by the ^{232}U daughter, ^{208}Tl. Depending on the material storage system used, the facility itself may serve as a radiation shield. The regulations pertaining to occupational radiation protection as specified in 10 CFR 835, shall be met.

5.4 SNM Safeguards

Uranium-233 is a weapons-usable material due to its fissile properties and its ability to be produced in sufficient quantities for manufacturing nuclear weapons. This material must be protected from unauthorized access and unauthorized use. Safeguards measures must meet the requirements of DOE O 470.1, DOE O 471.1, and DOE O 472.1B.

APPENDIX A
TECHINCAL BASES FOR
URANIUM-233 PACKAGING AND STORAGE CRITERIA

This Appendix provides the bases for the Standards presented in this document. The section numbers in this Appendix correspond to the sections in the body of the Standard.

1. INTRODUCTION

1.1 Purpose and Scope

This Standard establishes the criteria for safely packaging, transporting, and storing ^{233}U-bearing solid materials at ORNL and INEEL for at least 50 years. Uranium-233-bearing solid forms include metals, alloys, oxide powders, cermets, ceramic oxide pellets, and oxide monoliths. It does not apply to ^{233}U-bearing liquids, residues, waste, irradiated fuels, or to ^{233}U materials in-process (i.e., laboratory quantities involved in R & D studies).

Much of the material covered by this Standard is nearly isotopically pure ^{233}U with small amounts of ^{232}U; isotopes of uranium that may be present (with their half-lives in parentheses), include ^{238}U(4.5 x 10^9 y), ^{236}U(2.4 x 10^7 y), ^{235}U(7.0 x 10^8 y), ^{234}U(2.4 x 10^5 y), ^{233}U(1.6 x 10^5 y), and ^{232}U(69 y). Uranium-233 and its associated sister isotope ^{232}U are man-made and present much more severe radiological hazards than any of the naturally occurring uranium isotopes.

1.2 Equivalency

The basis for equivalency must be a technical justification for any departure from specific provisions of the standard.

2. DEFINITIONS

The terms and acronyms applicable to this Standard are adopted from relevant titles of the Code of Federal Regulations (CFR) and the Handbook of Acronyms, Abbreviations, Initialisms, Proper Names and Alphanumerics Encountered in Nuclear Safety Literature, March 1993.

3. REFERENCES

No Basis Required.

4. MATERIAL AND PACKAGING CRITERIA

4.1 Material Quantities

a. Nuclear Criticality Safety Approvals (NCSAs) must be obtained for the specific ^{233}U-bearing storage configurations for quantities in excess of minimum critical masses listed in ANSI/ANS-8.1. For example, the minimum critical mass for ^{233}U metal is 6.0 kg. The NCSAs must consider the presence of other fissile isotopes and materials, such as low-Z materials, plastics, and moisture, which potentially affect criticality. Neutrons are not directly produced during the radioactive decay of any of the uranium isotopes or the sequential decays. However, alpha-neutron reactions, in which alpha particles react with light isotopes such as ^{6}Li, ^{7}Li, ^{9}Be, ^{10}B, ^{19}F, ^{27}Al and ^{28}Si, generate neutrons.

   At ORNL there are limitations on the criticality safety limit based on the presence of hydrogen in the packaging material. (ORNL Criticality Safety Approval No. NSR 0032CT07008ABCD). The tube vault loading shall be within the following limits (for total uranium) derived from ORNL/TM-12374:

H/X* Range	Loading Limit (kg U/ft)
$H/X \leq 3$	2.00
$3 < H/X \leq 5$	1.80
$5 < H/X \leq 10$	1.45
$10 < H/X \leq 20$	1.00
$20 < H/X \leq 50$	0.50
$50 < H/X$	0.19

*H/X refers to the hydrogen-to-fissile atom ratio based on all materials within the container.

b. The individual package quantity guidance for ^{233}U is based on Safeguards Category III upper limits (DOE 5633.3B). Safeguards Category III (and IV) quantities of special nuclear material (SNM, i.e., fissile materials, including ^{233}U, which can be produced in quantities sufficient for weapons production) require substantially less rigorous levels of physical security and personnel security assurance than Safeguards Category II or I quantities of SNM.

The upper limits (Table A-1) for Safeguards Category III quantities of ^{233}U are <0.4kg for pure products (which include metals, weapons components and some metal fuel elements) and <2kg for high grade material (which includes carbides, oxides, fluorides, fuel elements and assemblies). If the Safeguards Category III upper limit is exceeded for individual packages, then enhanced security provisions must be afforded for all handling and storage of such packages.

Table A-1. SNM categories and attractiveness levels

Material	Attractiveness Level	Pu/^{233}U CATEGORIES (Kilograms) I	II	III	IV
Weapons and Test Devices	A	All Quantities			
Pure Products Metals, Components, Some Metal Fuel Elements	B	≥ 2	≥ 0.4 to < 2	≥ 0.2 to < 0.4	≥ 0.2
High Grade Material Carbides, Oxides, Fluorides, Fuel Elements & Assemblies, >25g/l solution	C	≥ 6	≥ 0.4 to < 2	≥ 0.2 to < 0.4	≥ 0.2
Low Grade Material 1-25 g/l Solutions, Recyclable Process Residues, Moderately Irradiated Mat.	D		≥ 16	≥ 3 to < 16	< 3
All Other Materials Highly Irradiated Materials, ≤ 1 g/l Solutions	E				Reportable Quantities

4.2 Material Criteria

4.2.1 <u>Metals and Alloys.</u> Potentially pyrophoric metals are not acceptable storage forms because this could lead to fires and dispersal of the uranium. Metallic uranium in massive form presents little fire hazard, but it will burn if exposed to a severe, prolonged fire. By contrast, finely divided uranium metal powder is pyrophoric (L. Bretherick, *Hazards in the Chemical Laboratory*, 1986), and can ignite spontaneously, if confined in a container without liquid or without air movement. The presence of moisture in the gas phase over exposed chips increases this possibility (J. J. Burke, et al. *Physical Metallurgy of Uranium Alloys*, 1976). The flammability of uranium depends almost entirely on the specific surface area. Finely divided uranium metal ignites spontaneously upon exposure to air and burns rapidly to the oxide. For uranium foils and wires, the experimentally determined ignition temperatures are somewhat higher than for powders having the same specific surface area. The recommended upper limit of specific surface area is 50 cm^2/g, based on the analysis presented in Section 4.9 of the *Draft Hazard Analysis for Storage of ^{233}U*. This is considered a conservative value since the corresponding ignition temperature of about 255 °C is far above temperatures expected to be achieved during storage. Uranium metal pieces larger than sieve mesh size 8 (2.38 mm) are assured of having a specific surface of less than 50 cm^2/g and may be stored in tube vaults. Uranium metal of less than sieve mesh size 8, powders, thin foils, and turnings of uranium are potentially pyrophoric and must be converted to stabilized oxide prior to storage or must be stored in a sealed container with an inert atmosphere (ANL-6287).

Some loose removable oxides associated with metals may also be pyrophoric. An adherent oxide layer on stored metal is generally beneficial because it tends to retard further oxidation. However, as UO_2 (the first oxide produced), this coating may be pyrophoric. Therefore, prior to repackaging ^{233}U metal, readily removable loose oxide must be removed from outer metal surfaces.

4.2.2 <u>Separated Oxide Powder.</u> Water and other liquids present in the $^{233}UO_2$ material can cause corrosion of the container and reduce its integrity. Corrosion, or oxidation, of metal by water produces hydrogen gas, which could lead to pressurization of the container. Liquids are also subject to radiolysis that would result in increased pressure within the container. The complete radiolysis of one gram of water produces 1.87 liters of gas at standard temperature and pressure. Therefore, only uranium oxides that have been thermally stabilized to remove moisture and to convert residual salts are acceptable for storage without further stabilization.

Materials that could pressurize the inner storage container during storage are not acceptable for storage and must be thermally stabilized. Uranium oxide powders can have a high surface area depending on preparation conditions. All three predominant uranium oxide forms are acceptable for storage. The most desirable form is U_3O_8 because it potentially can adsorb less moisture per U atom than other oxides (UO_2, UO_3). The potential storage hazard concern associated with adsorbed moisture is the ultimate pressurization of a sealed oxide container over a prolonged period through any of several radiolytic and chemical processes. The adsorbed moisture also could be a potential problem for criticality if the associated moderation is not considered.

TBD - U_3O_8, UO_2 and UO_3 were prepared, packaged or stored in Building 3019 in a manner suitable for long term storage. However, UO_3 hydrates readily. Calculations will be performed to determine the practical feasibility of reactions that could take place based on stoichiometric data.

The initial moisture content (upon packaging) is important from the standpoint of trapped volatiles that might pressurize the container upon radiolysis. Moisture might be picked up by the material from humidity in the atmosphere in which packaging is performed.

4.2.3 **Oxide Monoliths.** Oxide monoliths have been formed at ORNL by a denitration technique (McGinnis, et al. 1986) that excludes enhanced fluidization, which would promote powder formation, and have been calcined to an oxide at greater than 700 °C for at least one hour. Formation of the oxide monoliths under these conditions assures that there are essentially no fine particles available for dispersion and respiration upon release and that there are only minimal amounts of moisture or nitrates present. Low quantities of moisture and nitrates will significantly reduce the potential formation of excessive amounts of gases by radiolysis and/or degradation.

4.2.4 **Ceramic Oxides.** Ceramic mixed oxide pellets have been formed at sufficiently high temperatures (> 1750 °C) that they are free of residual moisture or salts. The lack of fine materials in these products precludes them from being dispersible. The ceramic oxides are highly resistant to oxidation and require no further stabilization to be acceptable for storage [WAPD-TM-1244(L)].

The ^{233}U inventory at INEEL includes ceramic mixed oxide pellets, and unirradiated fuel rods composed of Zircaloy-clad ^{233}U-bearing ceramic pellets from a former fuel cycle program. The mixed oxide ceramics consist of an average 97% thorium and 3% ^{233}U oxides.

Pellets were fabricated by high pressure compaction of finely ground ^{233}U oxide with finely ground thorium oxide powders into cylindrical pellets. These pellets were sintered at temperatures in excess of 1750°C (3182°F) for at least 12 hours to form pellets that resist chemical and physical degradation. The densities of these pellets are approximately 98% of theoretical (>10.6 g/cm^3), effectively self-shielding emitted alpha radiation, inhibiting particulate dispersal, and serving as a containment for the incorporated ^{233}U oxide.

Finished, unirradiated fuel elements (Zircaloy-clad pellets) further enhances the safety and safeguards character of the ^{233}U-bearing processed material.

4.3 Packaging for Storage

The design goal for the storage package is that it should be essentially maintenance free and should allow shipping without further processing or repackaging.

Four packaging system configurations, consistent with the defense-in-depth concept applied at INEEL and ORNL, for safe storage of ^{233}U can be used. These configurations are illustrated in Figure 1. The four options are described as follows:

Option 1 - The ^{233}U-bearing materials packaging system consists of a material container, a primary container (the first barrier), and a containment vessel (the second barrier). The facility (e.g., the storage matrix and lead shielding) provides shielding to reduce the photon radiation fields to levels compliant with occupational radiation protection requirements.

Option 2 - The ^{233}U-bearing materials packaging system consists of a material container (the first barrier) and a containment vessel (the second barrier). The facility (e.g., the storage matrix and lead shielding) provides shielding to reduce the photon radiation fields to levels compliant with occupational radiation protection requirements.

Option 3 - The ^{233}U-bearing materials packaging system consists of a material container and a primary container (the first barrier). With this packaging configuration, the facility (the second barrier) provides shielding to reduce the photon radiation fields to levels compliant with occupational radiation protection requirements as well as containment.

Option 4 - The ^{233}U-bearing materials packaging system consists of a material container (the first barrier). With this packaging configuration, the facility (the second barrier) provides shielding to reduce the photon radiation fields to levels compliant with occupational radiation protection requirements, as well as containment.

4.3.1 General Requirements

a. Materials of construction must be selected so that their resistance to corrosion ensures structural integrity for prolonged periods of storage. Corrosion of the container during storage is a potential problem for two primary reasons: (1) if the corrosion is significant, it could result in loss of strength of the container or permit loss of containment of the packaged material; and (2) the resulting hydrogen evolution could cause container pressurization and pose a fire or explosion hazard. The facility is responsible for ensuring that the selected material of construction is appropriate to the environment.

b. Any non-corrosive atmosphere is acceptable for packaging solid materials. However, an inert or nitrogen atmosphere is needed for metals to ensure that metal surfaces are not oxidized - the form of which can be reactive. (J. J. Dawson, et al., 1956)

c. Permanent markings ensure the integrity of identification for material control. (DOE 5633.3B)

d. ***TBD - Container closure remains an issue for the Standard and revolves on addressing two hazards: (1) preventing container failure due to pressure buildup from radiolytic gas evolution, and (2) preventing outer container contamination levels from particles and evolved ^{220}Rn from exceeding limits set in 10 CFR 835.***

Container pressurization is caused by a combination of radon and helium production by alpha decay, radiolysis of water and other hydrogenous materials, and corrosion of the uranium and/or the container. The rate of container pressurization due to alpha decay is small, but radiolysis of water will generate a greater volume of hydrogen and oxygen gas. This mixture creates a potential explosion hazard as well as a possible source of container pressurization. Corrosion of uranium metal also results in hydrogen evolution contributing to container pressurization.

Theoretical pressurization calculations were conducted for an actual container of Consolidated Edison Uranium Solidification Project (CEUSP) material (the largest single container quantity of U with ^{233}U at ORNL). The calculations considered pressure buildup due to radiolytic decomposition of water, the accumulation of radon and helium from radioactive decay, and increases in temperature during storage. The material in the container consists of 3.742 kg U_3O_8 comprising ^{232}U (132 ppm), ^{233}U (9.7 wt %), ^{234}U (1.4 wt %), ^{235}U (76.5 wt %), ^{236}U (5.6 wt %), and ^{238}U (6.8 wt %). The maximum temperature of the material in the can is calculated to be 104 °F (40 °C).

Based on the assumption that the U_3O_8 has been in contact with moisture to form $U_3O_8(OH)_2$, the complete radiolysis of the water would result in a predicted pressure of 625

psia at a temperature of 104°F. A second set of preliminary calculations was made for this can of material assuming that the radiolysis of water to form hydrogen and oxygen gas was limited by the deposition of alpha and beta energy from the decay of the various uranium isotopes and their decay series over a period of 50 years. These preliminary calculations indicated that the pressure buildup would be on the order of 70 psia.

There is no radon produced in the decay of ^{233}U, but the decay chain of ^{232}U includes the isotope ^{220}Rn, which has a half-life of 55.6 sec. Other uranium isotopes (^{238}U, ^{236}U, ^{235}U, and ^{234}U) are likely to be present in the stored material. Isotopes of natural uranium, except for ^{235}U, produce ^{222}Rn, which has a half-life of 3.82 days. The accumulation of radon contributes negligibly to the pressure buildup and helium accumulation produces a pressure of 0.123 psia. Transport mechanisms will be evaluated for radon emanation from a sealed can. Sealing may potentially be measured by analyzing for ^{220}Rn and its alpha decay products. A representative number of samples for a group of packages should be inspected.

4.3.2 Inner Container. Two containers are needed to provide a defense-in-depth for ^{233}U metals and powders in prolonged storage. The inner container serves as the primary barrier isolating the stored dispersible material from the environment. Dimensional limits, based on the outer container design, are such that positive closure of the inner container is facilitated. The facility operator is responsible for ensuring compatibility with the outer container. At ORNL, the inner container should be no greater than 8.6 cm (3.375 in.) I.D. (ORNL/TM-12374) and sized to fit into the outer container.

4.3.3 Outer Container.

a. The outer container is sized to fit into tube vaults and existing shipping containers. Consideration of compatibility with transport casks will minimize future handling and avoid unnecessary additional personnel exposure, operational risk and waste generation.

   At ORNL, the dimensional requirements for the outer cylindrical container should be as follows:

   1. Maximum outside diameter <11.0 cm (4.4 in).
   2. Minimum external height >10.1 cm (4.0 in).

   The minimum height ensures that the container will not tumble when placed into the tube vault.

b. External surfaces of the outer container shall be as free from contamination as practical. Exterior surface contamination may be evidence of potential leakage of radioactive materials. (10 CFR 835)

c. The storage container should be designed to maintain its physical integrity, including its seal, during anticipated handling.

4.3.4 Optional Container(s). To facilitate material handling, additional packaging layers may be used for convenience.

4.3.5 Oxide Monoliths. The resistance of these materials to dispersal of both radon and solid particulates is considered sufficient.

4.3.6 Ceramic Fuel Materials

Mixed oxide pellets were fabricated by high pressure compaction of finely ground ^{233}U oxide with finely ground thorium oxide powders into cylindrical pellets. These pellets were sintered at temperatures in excess of 1750°C (3182°F) for at least 12 hours to form pellets that resist chemical and physical degradation. The densities of these pellets are approximately 98% of theoretical (>10.6 g/cm^3), effectively self-shielding emitted alpha radiation, inhibiting particulate dispersal, and serving as a pseudo-containment for the incorporated ^{233}U oxide.

Finished, unirradiated fuel elements (Zircaloy-clad pellets) further enhances the safety and safeguards character of the ^{233}U-bearing processed material.

4.4 Inspection and Surveillance for Safety

No additional basis required.

4.5 Documentation

No additional basis required.

4.6 Quality Assurance

No additional basis required.

5. STORAGE FACILITY FEATURES

5.1 Nuclear Criticality Safety

A principal safety consideration for the storage of ^{233}U is eliminating the possibility of the material reaching a configuration that would result in criticality. Criticality avoidance is a prime priority in safety considerations in the design and operation of a ^{233}U storage facility. In addition to providing an array that is initially criticality safe, the facility must be engineered to avoid the occurrence of sustained fission under upset conditions such as fires, flooding, earthquakes, and tornadoes. Because criticality safety is considered to be the dominant safety concern in the design and operation of a ^{233}U storage facility, the vault area should be designed with consideration of water sources such as fire sprinklers. Co-existing combustible materials should be minimized or eliminated from the facility in order to minimize the potential for fires and the need for fire suppression systems.

A majority of the ^{233}U in inventory consists of mixtures of ^{233}U and ^{232}U or mixtures whose properties are dominated by the ^{233}U and ^{232}U content. Uranium-233 has substantially different nuclear criticality properties than the other two Special Nuclear Materials (SNMs), ^{235}U and ^{239}Pu. Therefore, facilities designed for ^{235}U and ^{239}Pu may not be acceptable for comparable activities involving ^{233}U from a nuclear criticality safety standpoint and must be evaluated to meet the requirements for criticality safety specified in DOE O 420.1.

5.2 Confinement of Contamination

The matrix of the material and/or the inner container provide the first barrier against spread of contamination; the outer container and the tube vaults provide additional barriers. The packaging should be designed to maintain mechanical integrity, including its seal, during normal handling.

However, this package is not expected to provide protection against all perils such as major fires and earthquakes; design of the facility and of the storage array are expected to address these considerations.

5.2.1 Facility Confinement.

a. No additional basis required.

b. No additional basis required.

c. Uranium-233-bearing material storage facilities shall meet the National Fire Protection Association (NFPA) standards, as applicable (DOE O 420.1). Because criticality safety is considered to be the dominant concern in the design and operation of a ^{233}U storage facility, the vault area should be designed to provide isolation from fire sprinklers or other sources of water. The facility should be constructed using non-flammable materials (principally concrete). DOE 5480.7 requires the evaluation of combustible loading during the Fire Protection Design Analysis. It is generally best to eliminate all combustible materials from the facility and thus minimize the need for fire suppression.

d. No additional basis required.

e. No additional basis required.

f. No additional basis required.

g. No additional basis required.

5.2.2 Ventilation. Physical confinement of ^{233}U is provided by the ^{233}U-bearing materials packaging and the facility where the material is stored. The ^{233}U-bearing materials packaging and storage facility serve as multiple barriers to protect the workers and members of the public from inadvertent exposure to ^{233}U, the contaminant ^{232}U, and the radioactive daughters of these two uranium isotopes. Since several packaging configurations can be used for the ^{233}U-bearing material, the packaging along with the storage facility, represent a defense-in-depth confinement system.

An additional barrier for material confinement can be provided by the facility ventilation system. The ventilation system moves air from clean to contaminated areas within the facility and then the air is discharged from the facility though a system of holding cells, filters, and an off-gas stack. This filtration system ensures that the requirements for stack emissions in 40 CFR 61, Subpart H are met.

5.3 Radiation Shielding

Uranium-233 with its associated sister isotope ^{232}U present much more severe external radiation hazards than any of the naturally occurring uranium isotopes. Massive biological shielding is required, in most cases, to protect personnel from the 2.6 MeV gamma emission of ^{232}U daughter product ^{208}Tl.

Neutrons are not directly produced during the radioactive decay of any of the uranium isotopes or the sequential decays. However, alpha-neutron reactions, in which alpha particles react with light isotopes such as ^{6}Li, ^{7}Li, ^{9}Be, ^{10}B, ^{19}F, ^{27}Al and ^{28}Si, generate neutrons. Depending on the material storage system used, the facility itself may serve as a shield.

In addition the occupational radiation exposure must be kept as low as reasonably achievable (ALARA). In defining ALARA, the National Council on Radiation Protection and Measurements (NCRP) states that "ALARA is simply the continuation of good radiation-protection programs and practices which traditionally have been effective in keeping the average and individual exposures for monitored workers well below the limits." NCRP "did not intend that application of the ALARA principle be raised to such extremes so as to restrict unnecessarily the use of radiation in the occupations of commerce and medicine and consequently preclude its employment when there are countervailing benefits to be gained."

External radiation dose rates at 1 ft. from the surface of a nominal 6 in. x 6 in. cylindrical container containing a nominal 1 kg ^{233}U with ^{232}U concentrations ranging from 5 to 200 ppm decayed over 10 years (at which time the maximum gamma radiation occurs) are shown in Figures A-1 and A-2. Two types of shielding materials, lead (with a density of 11.34 g/cm^3) and concrete (with a density of 2.35 g/cm^3), and of varying thickness are used. The figures are intended to provide a general indication of dose rates that can be expected for 1 kg of ^{233}U. Since actual dose rates are dependent on the source (e.g., activity, geometry, and matrix), shielding, and source-to-detector configuration, expected dose rates for actual conditions should be determined on a case-by-case basis.

5.4 **SNM Safeguards.** No additional basis required.

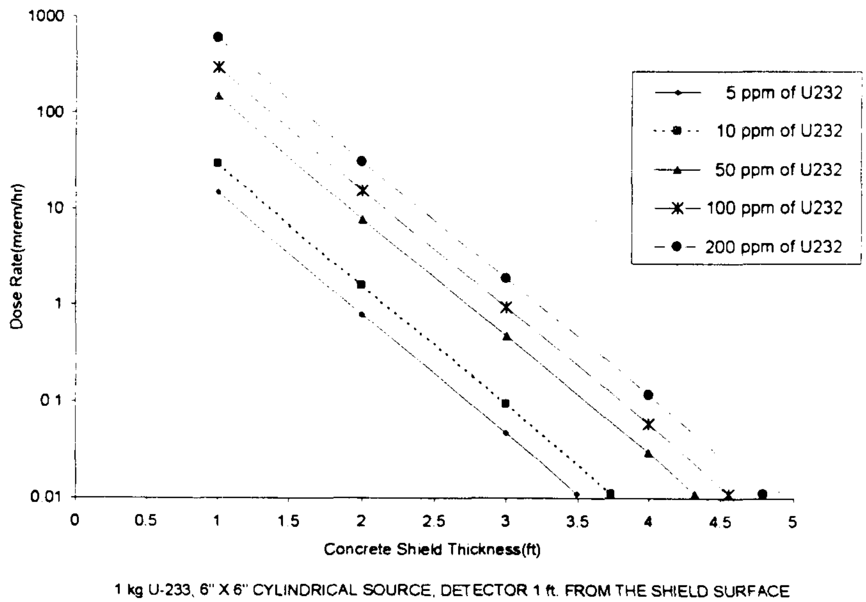

Fig. A-1. Dose rate at 1 ft. vs. concrete shield thickness.

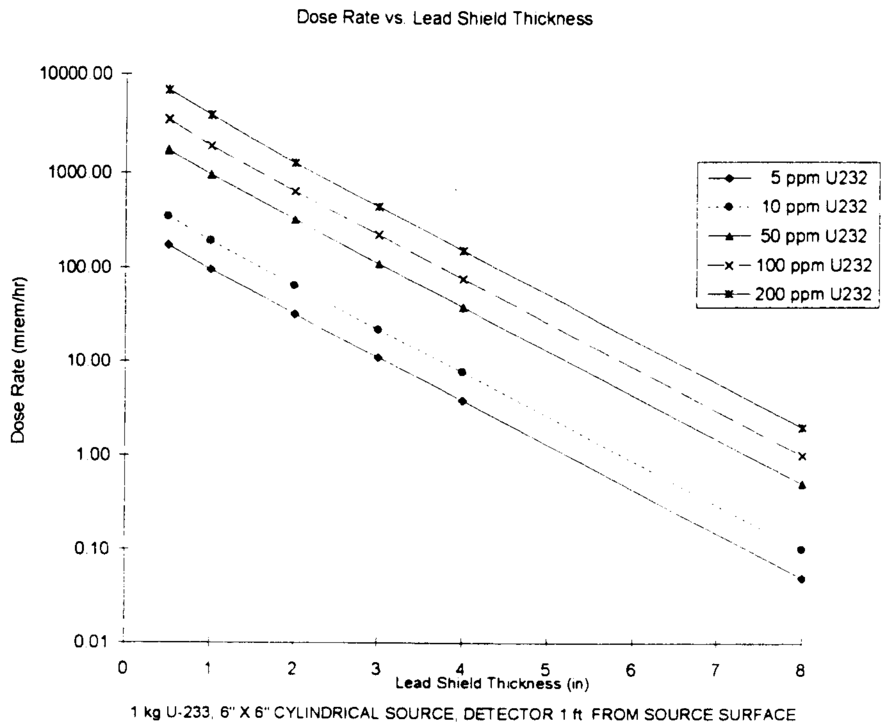

Fig. A-2. Dose rate at 1 ft. vs. lead shield thickness.

APPENDIX B
GLOSSARY AND ACRONYMS

1. GLOSSARY

Acceptable - Conforming with safety requirements, directives, or regulations.

Accounting - That part of Safeguards and Materials Management that encompasses the management system and records and reports to account for source and special nuclear material to minimize the possibility of diversion and to detect diversion promptly should it occur. Accounting does not include physical protection.

ALARA (As low as reasonably achievable) - The implementation of good radiation-protection programs and practices which traditionally have been effective in keeping the average and individual exposures for monitored workers well below allowable limits.

Alloy - A substance composed of two or more metals united by being fused together and dissolving in each other when molten.

Application of Safeguards (To Materials or Facilities) - The implementation of appropriate safeguards system under the Nonproliferation Treaty with a view of preventing diversion of nuclear energy from peaceful use to nuclear weapons or other explosive devices.

Approved - Acceptable to the "authority having jurisdiction."

Authority Having Jurisdiction - The organization, office, or individual responsible for approving equipment, installation, or procedure.

Barrier - A restraint that provides containment of stored material and protection from the environment.

Calcine, Calcining - The process of heating materials to remove combustible or volatile materials such as organic matter, salts, and moisture.

Ceramic - A class of inorganic, nonmetallic solids formed at high temperature (>1000°C) in manufacture or use.

Cladding - An outer metal jacket or can that surrounds and protects fuel pellets containing source and special nuclear material. Typical cladding materials are alloys of aluminum or zirconium and stainless steel.

Combustible - In the form used and under the conditions anticipated, will ignite, burn, support combustion, or release flammable vapors when subjected to fire or elevated temperature.

Conversion - An operation for changing from one material form, use, or purpose to another.

Database - A large collection of data in a computer, organized so that it can be expanded, updated, and reviewed rapidly for various uses.

Dilution - In general the addition of inert material or solvent with the result that the concentration of the material of interest is reduced.

Effective Neutron Multiplication Factor (k_{eff}) - The ratio of the total number of neutrons produced during a time interval (excluding neutrons produced by sources whose strengths are not a function of fission rate) to the total number of neutrons lost by absorption and leakage during the same time interval.

Enclosure - A physical structure that provides a barrier between the internally contaminated package and the worker, facility, and environment.

Engineered Safety Feature - Systems, components, or structures that prevent and/or mitigate the consequences of potential accidents including the bounding design basis accidents.

Handling Enclosure - A glove box line or similar equipment that isolates ^{233}U-bearing materials from the worker's environment while allowing the material to be handled or processed.

Hot Cell - A heavily shielded enclosure in which radioactive materials can be handled by persons using remote manipulators and for viewing the materials through shielded windows or periscopes.

Inert Gas - A non-reactive gas or combination of gases appropriate to the material being stored that will not support corrosion of the container or oxidation of its contents.

In-Line - Something located inside a material handling enclosure (e.g., glove box or "hot" storage vault). When material is stored "in-line," the enclosure provides one barrier for storage.

In-Process, In-Use Material - Material that is integral to the continuing manufacture or recycle operations of the nuclear weapons complex and may not be considered as excess material for storage.

Low-Z Material – Elements of atomic mass 12 or less.

Material Container - The container that is in contact with the uranium material being stored. If structurally adequate and sealed, the material container provides one barrier.

Non-Destructive Assay (NDA) - A procedure (e.g., calorimetric or radiometric measurement) for determining the amount of fissionable uranium in a container without physically sampling the material.

Non-Destructive Examination (NDE) - A procedure (e.g., radiography) for examining the contents of a container without opening the container.

Nonproliferation Treaty - A Treaty (to prevent the spread of nuclear weapons) presented to the Eighteen-Nation Disarmament Committee in Geneva by the U. S. and USSR in identical texts on January 18, 1968. The Treaty entered into force March 5, 1970.

Nuclear Criticality Safety - The prevention or termination of inadvertent nuclear criticality and protection against injury or damage due to an accidental nuclear criticality.

Packaging - The assembly of materials and components in compliance with storage/shipment requirements.

Process - To extract, separate, purify, or fabricate a material by physical, chemical, or mechanical means.

Pyrophoric - Capable of igniting spontaneously when exposed to air.

Quality Assurance (QA) - All planned and systematic actions necessary to provide adequate confidence that a structure, system, or component will perform satisfactorily in service.

Residue - Process-generated uranium-bearing materials not classified as storable metal or stabilized oxide that contain a non-discardable quantity of uranium.

Sealed - Sealed means that a container has been closed (e.g., welded) and certified to be leak-tight in accordance with ANSI Ni4.5-1987 standard.

Shall, Should and May - "Shall" denotes that something is required. "Should" denotes that something is recommended but is not required. "May" denotes that something is permitted but is neither a requirement nor a recommendation.

Specific Surface Area - The ratio of the geometric surface area of a material to its mass in units of cm^2/g.

Standard Cubic Centimeter of Gas - The quantity (moles) of gas in one cubic centimeter of volume at 1 atmosphere pressure and 25°C (298 K).

Storage - Any method for safely maintaining items in a retrievable form for subsequent use or disposition.

Storage Facility - The building structure and other confinement systems that house storage containers.

Storage Package - A configuration of nested containers including package content.

Thermal Stabilization - A process that exposes a uranium-bearing material in air to an elevated temperature for the duration required to convert reactive constituents present to U_3O_8 and to remove adsorbed moisture and other volatile species.

Tube Vaults - Tubular storage devices (steel lined and encased in concrete) used for the storage of packages containing ^{233}U.

Unirradiated Material - Material that has not been subjected to the high-neutron-flux environment existing near the core of a nuclear reactor.

2. Acronyms

ALARA	As low as reasonably achievable
ANSI	American National Standards Institute
CFR	Code of Federal Regulations
DOE	U. S. Department of Energy
DOT	Department of Transportation
INEEL	Idaho National Engineering and Environmental Laboratory
LANL	Los Alamos National Laboratory
NCSA	Nuclear Criticality Safety Assessment
NDA	Non-Destructive Assay
NDE	Non-Destructive Examination
NMC&A	Nuclear Material Control and Accountability
ORNL	Oak Ridge National Laboratory
ppm	Parts per million, or grams of designated material per megagram (metric ton) of net representative sample
Pu	Plutonium
Rn	Radon
SNM	Special Nuclear Materials
Th	Thorium
Tl	Thallium
U	Uranium
UO_2	Uranium Dioxide
U_3O_8	Triuranium Octoxide

APPENDIX C

REFERENCES

REFERENCES

Specific DOE and other Federal agency regulations and other documents used in developing this Standard and the bases for the Standard are listed below.

1. Federal Regulations

The following Federal Regulations are referenced in this Standard:

10 CFR 20, Standards for Protection Against Radiation;

10 CFR 71, Packaging and Transportation of Radioactive Material;

10 CFR 830.120, Nuclear Safety Management, Quality Assurance Requirements;

10 CFR 835, Occupational Radiation Protection, Surface Radioactivity Values;

29 CFR 1910, Occupational Safety and Health Standards;

40 CFR 61 Subpart H, National Emission Standards for Emissions of Radionuclides Other Than Radon From Department of Energy Facilities

49 CFR 178, Specifications for Packaging.

Copies of Federal Regulations are available from the Government Printing Office (GPO), Superintendent of Documents, Mail Stop: SSOP Washington, DC 20402-9329

2. Department of Energy Orders, Manuals and Reports

The following DOE Orders, Manuals and Reports are referenced in this Standard:

DOE O 231.1, Environment, Safety, and Health Reporting, November 7, 1996;

DOE M 231.1, Environment, Safety, and Health Reporting Manual, September 30, 1995;

DOE O 420.1, Facility Safety, October 13, 1995;

DOE O 425.1, Startup and Restart of Nuclear Facilities, October 26, 1995;

DOE O 430.1, Life Cycle Asset Management, October 26, 1995;

DOE O 470.1, Safeguards and Security Program, June 21, 1996;

DOE O 471.1, Unclassified Controlled Nuclear Information, September 25, 1995;

DOE O 472.1B, Personnel Security Activities, March 24, 1997;

DOE 5400.1, General Environmental Protection Program, June 29, 1990;

DOE 5480.3, Safety Requirements for Packaging and Transportation of Hazardous Materials, July 1985;

DOE 5480.7A, Fire Protection;

DOE 5480.21, Unreviewed Safety Questions, December 1991;

DOE 5480.22, Technical Safety Requirements, January 23, 1996;

DOE 5480.23, Nuclear Safety Analysis Reports, March 1994;

DOE 5480.24, Nuclear Criticality Safety, August 1992;

DOE 5630.11B, Safeguards and Security Program, August 1994;

DOE 5633.3B, Control and Accountability of Nuclear Materials, September 1994;

DOE 5660.1B, Management of Nuclear Materials, May 26, 1994;

DOE/EH-0256T, U. S. Department of Energy Radiological Control Manual, Rev. 1, April 1994;

DOE/EH 0525, Safety and Health Vulnerabilities Associated with the Department's Storage of Highly Enriched Uranium, December 1996;

DOE/RW-0006-Rev.10, Integrated Data Base Report-1993 U. S. Spent Nuclear Fuel and Radioactive Waste Inventories, Projections and Characteristics, December 1994.

Copies of DOE Orders and reports are available from:

U.S. Department of Energy, AD-631/FORS, Washington, DC 20585, (202)586-9642

3. Nuclear Regulatory Commission (NRC) Documents

The following NRC documents are referenced in this Standard.

NUREG/CR-3019, Recommended Welding Criteria for Use in the Fabrication of Shipping Containers for Radioactive Materials, March 1984.

NUREG/CR-3854, Fabrication Criteria for Shipping Containers, March 1985.

NRC Inspection and Enforcement Manual, Inspection Procedures 61700, 61701, and 61725.

Copies of NRC documents are available from:

U.S. Nuclear Regulatory Commission
Public Document Room
2120 L Street, N.W.
Lower Level
Washington DC 20555-1000

4. Non-Federal References.

The following non-government documents are referenced in this Standard.

ANL-6287, Chemical Engineering Division, Argonne National Laboratory, Summary Report, March 1961;

ANSI 8.7, Guide to Nuclear Criticality Safety in the Storage of Fissile Materials, 1975 (Reaffirmed 1987);

M. J. Bannister, The Storage Behavior of Uranium Dioxide Powder, J. Nuclear Materials, 26, 174 (1968);

J. Belle, Uranium Dioxide: Properties and Nuclear Applications, 1961, Naval Reactors, Division of Reactor Development, USAEC;

BIO/3019-CTD/SSE/RO, Basis for Interim Operation Building 3019 Complex Radiochemical Development, October 1995 (Draft);

BMI-X-447, Hot-Hardness Measurements of ThO2/UO2 Fuel Pellets, 1969; **(Reference was recommended but not yet located)**

M. B. Bever (ed.), *Encyclopedia of Material Science and Engineering*, Vol.2, MIT Press, Cambridge, MA, 1986.

L. Bretherick, *Hazards in the Chemical Laboratory*, Royal Society of Chemistry, London, 1986;

R. E. Brooksbank, J. P. Nichols and A. L. Lotts, The Impact of Kilorod Facility Operational Experience on the Design of Fabrication Plants for ^{233}U-Th Fuels, Second International Thorium Fuel Cycle Symposium, Gatlinburg, TN, May 3-6, 1966. CONF-660524;

J. Burke, et al. *Physical Metallurgy of Uranium Alloys*, 1976

H. K. Clark, Subcritical Limits for Uranium-233 Systems, Nuclear Science & Engineering 81, 379-395 (1982);

J. J. Dawson, et al., *"Some Aspects of the System Uranium Trioxide - Water,"* J. Chem. Soc., 3531-3540, 1956.

DNFSB/Tech 13, Uranium-233 Storage Safety at Department of Energy Facilities, February, 1997;

DPST-89-337, Maximum Fissile Units for Handling ^{233}U, ^{232}U, and ^{239}Pu That Assure a 0.05 Margin in k_{eff}, D. R. Finch, March 1989; **(Reference was recommended but not yet located)**

W. Duerksen, *Draft Hazard Analysis for Storage of ^{233}U*, April 1998;

DUN-SA-11, J. M. Boswell, R. D. McCrosky, J. T. Stringer and W. K. Woods, Production of Uranium-233 with Low ^{232}U Content, May 3, 1966;

EGG-2530, Health Physics Manual of Good Practices for Uranium Facilities, June 1988;

C. D. Harrington and A. E. Ruhle, Uranium Production Technology, pp 44-52, D. Van Nostrand, New York, 1959.

LA-10860-MS, Critical Dimensions of Systems Containing ^{235}U, ^{239}Pu, and ^{233}U; 1986 Revision, H. C. Paxton and N. L. Pruvost, July 1987;

LA-3067-MS, Rev., Los Alamos Critical-Mass Data, H. C. Paxton, November, 1975;

C. P. McGinnis et al, A Remotely Operated Facility for In-Situ Solidification of Fissile U, Proc. Waste Management '86, March 2-6, 1986;

C. P. McGinnis, E. D. Collins, R. Hall, J. K. Johnson, A. M. Krichinsky, B. B. Patton, J. T. Shor, and R. J. Vedder, *"Development and Operation of a Unique Conversion/Solidification Process for Highly Radioactive and Fissile Uranium,"* Nucl. Technol., 77, 210-219, 1987.

J. P. Nichols, R. E. Brooksbank and D. E. Ferguson, Radiation Exposures in Fabricating ^{233}U-Th Fuels, Nuclear Applications vol. 1/2, 1965;

ORNL/CF-79/279, The Preparation of Kilogram Quantities of $^{233}UO_2$ for the Light Water Breeder Reactor Demonstration Program, J. R. Parrott, Sr., W. T. McDuffee, R. G. Nicol, W. R. Whitson, A. M. Krichinsky, September 1979;

ORNL/CF-81/37, Final Safety Analysis Report for the Radiochemical Processing Plant (RPP) Approved 8/23-24/84;

ORNL/MD/LTR-53, Uranium-233 Disposition Options: A Roadmap (Draft), C. W. Forsberg et al., October 14, 1996;

ORNL/MD/LTR-60, Strategy for the Future Use and Disposition of ^{233}U: Overview (Draft), C. W. Forsberg and A. M. Krichinsky, April 24, 1997;

ORNL/MD/LTR-62, Strategy for Future Use and Disposition of Uranium-233: Technical Information (Draft) P. J. Bereolos, C. W. Forsberg, D. C. Kocher and A. M. Krichinsky, June 12, 1997;

ORNL/TM-3469, Criticality Analysis: LWBR Assistance Program in Building 3019, Compiler, R. W. Horton, March 1972;

ORNL/TM-3567, Safety Analysis: LWBR Support Program in Building 3019 Pilot Plant, Compiler, R. W. Horton, March 1972;

ORNL/TM-5049, Assessment of the Radiological Impact of ^{233}U and Daughters in Recycled ^{233}U HIGR Fuel, J. E. Till, February 1976;

ORNL/TM-11016, Non-LWR and Special LWR Spent Fuels Characteristics and Criticality Aspects of Packaging and Disposal, R. Salmon and K. J. Notz, January 1990;

ORNL/TM-12152, Criticality Safety Studies for the Storage of Waste from Nuclear Fuel Services in Intercell Storage Wells 2 and 3 of Building 3019, R. T. Primm, III, C. M. Hopper, and G. R. Smolen, November 1992;

ORNL/TM-12374, Criticality Safety Studies of Building 3019 Cell 4 and In-Line Storage Wells, R. T. Primm, III, November 1993;

ORNL/TM-12720, Historical and Programmatic Overview of Building 3019, R. E. Brooksbank, Sr., D. B. Patton and A. M. Krichinsky, August 1994;

ORNL-4572, Chemical Technology Division Annual Progress Report, pp 174-178, May 1970.

ORNL-4682, Chemical Technology Division Annual Progress Report, pp 163-167, July 1971.ORNL-4755, Conversion of Uranium Nitrate to Ceramic Grade Oxide for the Light Water Breeder Reactor: Process Development, 1972;

ORNL-4755, Conversion of Uranyl Nitrate to Ceramic Grade Oxide for the Light Water Breeder Reactor Process Development, 1972.

ORNL-4794, Preparation of $^{233}UO_2$ for Light Water Breeder Reactors, 1972;

ORNL-6490, Chemical Technology Division Progress Report, January 1, 1987 to June 30, 1988.

A. G. Ritchie, "A Review of the Rates of Recation of Uranium with Oxygen and Water Vapor at Temperatures up to 300oC", Journal of Nuclear Materials **102**, 170 (1981).

N. I. Sax, *Dangerous Properties of Industrial Materials*, 3rd ed., van Nostrand Reinhold Company, New York, 1968.

TID-7650, Proceedings of the Thorium Fuel Cycle Symposium, Gatlinburg, TN, December 5-7, 1962;

R. J. Vedder, E. D. Collins and P. A. Haas, Development of the In-Can Thermal Denitration Step in the CEUSP Process, Proc. Waste Management '86, March 2-6, 1986;

WAPD-TM-789, Planetary Ball Milling as a Method of Comminuting Presintered Thoria/Urania Granules, 1969;

WAPD-TM-850, Gas Release from Thoria-Base Oxide Fuel Pellets, 1971;

WAPD-TM-1117, BMU Series of ^{233}U Fueled Critical Experiments (LWBR Development Program), 1975; **(Reference was recommended but not yet located)**

WAPD-TM-1172, Chemical and Spectrochemical Analysis of ThO_2 and $^{233}UO_2/ThO_2$ Pellets for the LWBR Core for Shippingport, 1975;

WAPD-TM-1244(L), ThO_2 and ThO_2-$^{233}UO_2$ High Density Fuel Pellet Manufacturer for the Light Water Breeder Reactor (LWBR Development Program), January 1976; **(Reference has limited distribution)**

X-OE-23 Natural Disturbance Analysis of Buildings 7930 and 3019, The Ralph M. Parsons Co., Pasadena, CA. March 30, 1979;

Y/ES-014/R4, Assessment of Enriched Uranium Storage Safety Issues at the Oak Ridge Y-12 Plant, August 1996;

Y/ES-015, Criteria for the Safe Storage of Enriched Uranium at the Y-12 Plant, S. O. Cox, July 1995;

Y/LB-15,913 Position Paper, Oak Ridge Y-12 Plant, Storage of Uranium in Plastics, W. K. Duerksen, July 1995;